PRELIMINARY DESIGN OF A 200 MJ PULSED POWER SYSTEM FOR A NAVAL RAILGUN PROOF OF CONCEPT FACILITY

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Abstract

The Navy's decision for implementation of an Integrated Power System into the next generation of surface combatants (DDX Warship) provides the opportunity for introduction of high powered electric weapons systems. An electromagnetic railgun is a candidate that provides enhanced capabilities for indirect fire support with increased ranges and velocities. Additionally, improvements of logistics for ammunition handling and storage make the railgun an attractive solution for the next generation Naval Electric Warship Armament.

The notional naval railgun at full scale will fire a 20 kg launch package at a velocity of 2500 m/s providing 63 MJ of muzzle energy. It is estimated that a 200 MJ pulse forming energy storage system (PFN) will be required to achieve the desired muzzle velocity and energy. A land based Proof-of-Concept (PoC) Facility can validate the notional railgun performance and pulsed power requirements. Components for the barrel, launch package, sabot and projectile designs will also be validated. Terminal effects can also be studied at the facility.

This paper describes preliminary design assessments associated with the 200 MJ Naval PoC Facility. Included are the facility requirements, PFN modeling and component technical assessment. Additionally the facility layout, capacitor bank modules and bussing requirements are illustrated.

I. PROOF-OF-CONCPET FACILITY MISSION & REQUIREMENTS

In order to meet its long-range and lethality requirements, the US Navy has adopted a notional railgun design that delivers approximately 63 MJ of projectile muzzle energy [1,2,3]. Currently, the Navy is pursuing a proof-of-concept effort to demonstrate the feasibility of this notional Naval railgun design, and a PoC facility is a key element in these demonstrations. Testing the rail launcher in different configurations and at different energy levels will be the main focus of the facility operations.

To support these activities, the following general requirements were imposed on the facility pulsed-power-system (PPS) design: (1) output current pulse-shape flexibility, (2) high degree of reliability, maintainability, and efficiency, (3) compact installation and operation, (4) modular design that allows incremental installation, and (5) operation from both within and outside SeaLand containers. The above requirements drove the PPS to be designed around a capacitor-based energy store. A further goal of this design was to advance the state-of-the-art of high-energy pulse-power systems – working towards meeting the requirements of a ship-based system. For example, solid-state switches were specified as the primary option for the design.

II. CAPACITOR DESIGN

The capacitors used in the PoC system will be 130kJ, 3000 shot capacitors operating at 1 J/cc. These capacitors will be built with self-healing metallized electrodes and represent an improvement in capability over currently available capacitors. The 130kJ PoC capacitors are derived from the 100 kJ, 0.7 J/cc design developed for the National Ignition Facility (NIF) and for which there is a large amount of supporting data dating back to the mid 1990's.

These capacitors will have the added flexibility to operate at multiples of 5.5kV. The capacitors will be built with two each 75kJ capacitors operating at 5.5 kV, packaged in a single can with four terminals isolated at 25kV. Connection of the

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14. ABSTRACT
The Navys decision for implementation of an Integrated Power System into the next generation of surface combatants (DDX Warship) provides the opportunity for introduction of high powered electric weapons systems. An electromagnetic railgun is a candidate that provides enhanced capabilities for indirect fire support with increased ranges and velocities. Additionally, improvements of logistics for ammunition handling and storage make the railgun an attractive solution for the next generation Naval Electric Warship Armament. The notional naval railgun at full scale will fire a 20 kg launch package at a velocity of 2500 m/s providing 63 MJ of muzzle energy. It is estimated that a 200 MJ pulse forming energy storage system (PFN) will be required to achieve the desired muzzle velocity and energy. A land based Proof-of-Concept (PoC) Facility can validate the notional railgun performance and pulsed power requirements. Components for the barrel, launch package, sabot and projectile designs will also be validated. Terminal effects can also be studied at the facility. This paper describes preliminary design assessments associated with the 200 MJ Naval PoC Facility. Included are the facility requirements, PFN modeling and component technical assessment. Additionally the facility layout, capacitor bank modules and bussing requirements are illustrated.

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terminals in various combinations allows operation at 5.5kV, 11kV, 16.5kV, or 22kV to full stored energy. While the PoC bank is designed to operate at 11kV these capacitors provide the flexibility to operate at different voltages in the future.

III. PFN DESIGN

The PoC pulse-forming network is required to operate at multiple levels of stored energy with a high degree of flexibility. This is due in part to the incremental installations of the PFN and the staged build-up of the facilities infrastructure. The PFN design must be able to address a variety of launcher inductance gradients and muzzle energies at the 8 MJ, 16 MJ, 32 MJ and finally the full 63 MJ capability.

A circuit model was created using MicroCap software to validate PFN performance at each of the installation increments. The model was validated against existing shot data from actual firings at the Green Farm Test Facility [4,5], Advanced Armature Program (AAP) predictions and some Pro Basic modeling. The circuit model consisted of up to 10 firing stages and contains all circuit elements including all the bank module components, buswork, as shown in Fig. 1. Additionally, cables and a gun model were included as shown in Fig. 2.

Modeling confirmed the system design parameters for the PoC banks were capable of reaching the desired launch package velocities and achieving the required muzzle energies for all of the installation increments. Fig. 3 shows the system current vs. time plot for the 32 MJ muzzle level (half scale) gun firing. This assumes a 10 kg launch package fired at 2500 m/s and requires 5-MA peak current for a 10-meter long launcher with an L′ of .45 μH per meter.

The module design configuration was selected based on the system requirements and a configuration trade study of performance, cost and safety considerations. A review of former bank module designs was performed to determine the est approach for the PoC Facility. Included in the review were examinations of the Kirkcudbright 32 MJ bank modules [6], the TZN bank modules [7] and the ARL 4.5 MJ bank modules [8].

The basic building block of the 200 MJ bank is a 3 MJ module. The module consists of 24 – 11 kV, 130 kJ capacitors, at 1 J/cc energy density, as shown in Fig. 4. Each of the capacitors is fused. Solid-state thyristors are a key feature to the system, providing greater overall system efficiency than arc gap type switches. The thyristors are switched into a 60 μH inductor, which provides pulse shaping and limits the output current to match the solid-state device and output bus capabilities. Each module is a self-contained pulsed power system, consisting of its own controls, trigger, and freewheeling diodes, charging power supply, soft and hard dump system. This allows the modules to be stand-alone systems and interface with the main control and safety systems.

A. Solid State Switches

The solid state switches for the modules require three parallel stacks of five series devices for a life cycle of 6500 pulses. The switch peak current equals 254 kA, action equals 113 MA^{2}sec, and the dI/dt is equal to 165A/μs. These parameters are achieved with a rise in junction temperature of 110 degrees C.

B. Diode Stacks

The freewheeling (crowbar) diode stacks will be placed

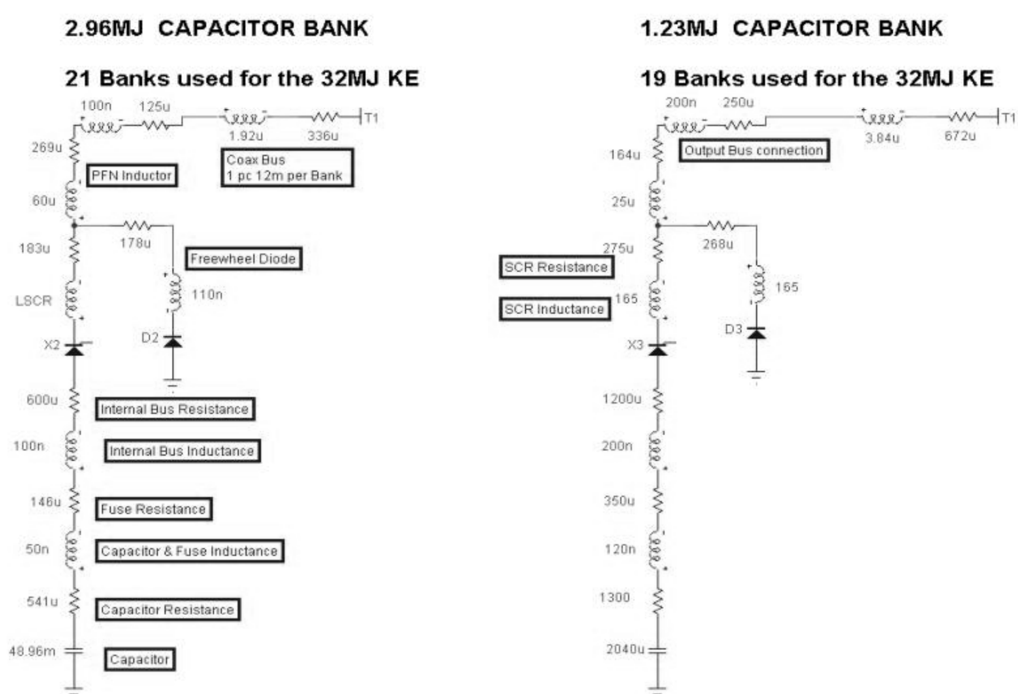

Figure 1. Module and Buswork Model

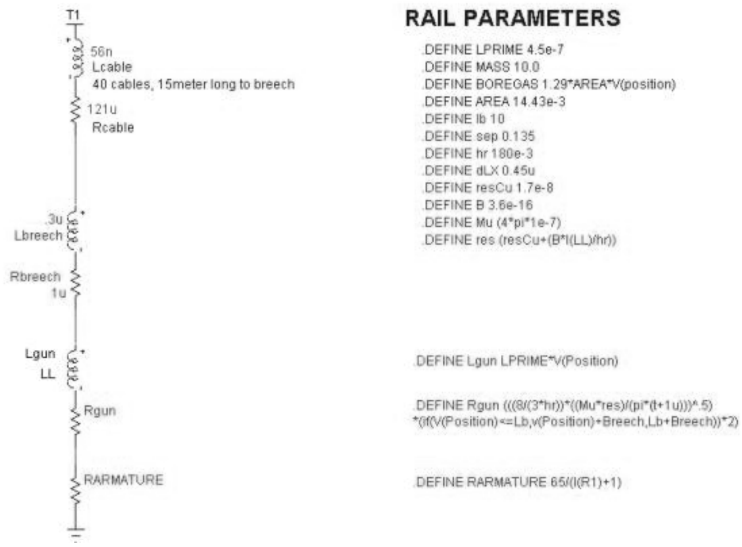

Figure 2. Cable and Gun Model

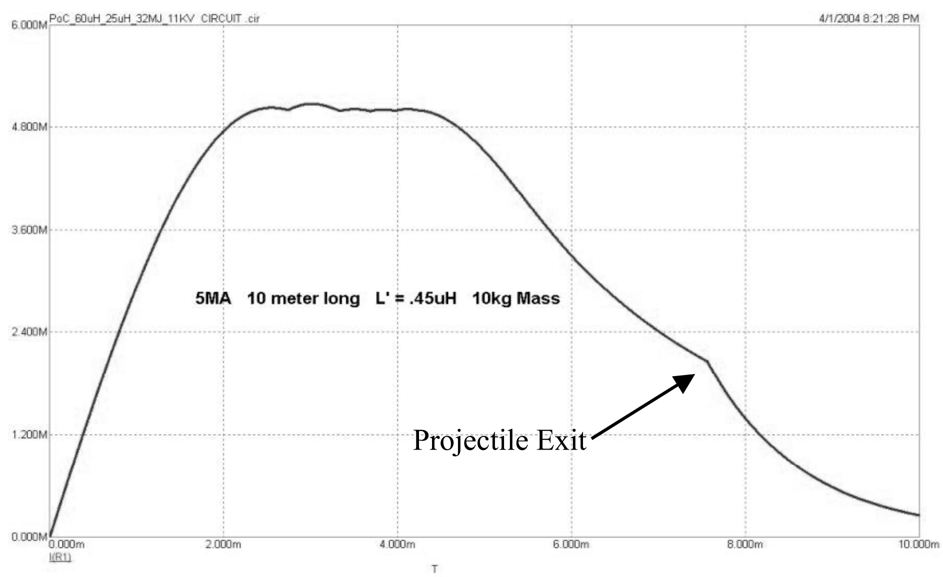

Figure 3. 32 MJ Muzzle Energy – Current Vs Time

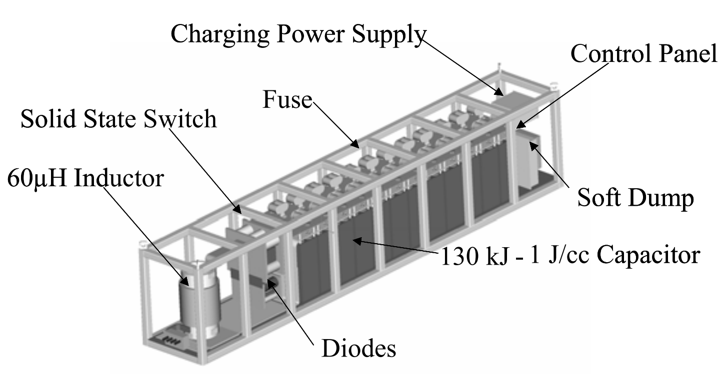

Figure 4. 3 MJ Module

outboard of switch in the circuit. This will require three parallel stacks of five series devices for a life cycle of 9,000 pulses with a rise in junction temperature of 105 degrees C.

C. Soft Dumps

Soft Dumps provide a slow discharge of the residual energy stored in the capacitors after a shot or after charging the banks and aborting the test. Dumping cycle is initiated by the closing of a high voltage relay. The energy is dumped through a 730-ohm resistor, providing a 12 second e-fold voltage decay.

D. Hard Dumps

Each module will be equipped with a hard dump safety system. Hard dumps will be pneumatically operated solenoids with a gang of electrical contacts that short the capacitor terminal on the capacitor side of the fuse connection. This provides personnel safety when a fuse is blown prior to full discharge of the capacitor.

E. Inductors

Two styles of inductors are incorporated into the modules, a 25μH inductor and a 60μH inductor. The different values are used in different module configurations to provide additional pulse shaping capabilities and better overall system efficiency. The "fast modules" are triggered later in the firing sequence and help maintain the flat top of the pulse shape. Fast modules consist of 1.3 MJ modules that are switched into the 25μH inductor. Two of the "fast modules" are contained in one rack, but are independently triggered.

Additionally the "fast modules" provide a quicker decay time, which limits the gun muzzle exit current. Modeling indicates it will require a combination of 55 – 3 MJ modules and 28 "fast" – 1.3 MJ modules to achieve 63 MJ of muzzle energy for full -scale demonstrations.

IV. CONTROLS & SYSTEM INTEGRATION

The PFN system is composed of 55, 3MJ modules and 28, 1.3 MJ modules. Each is a complete module capable of standalone operation that includes operation of energy storage dump components, configuration and operation of a capacitor charging supply, monitoring of various module status indicators, triggering of the PFN module and acquisition of various diagnostic signals. This represents literally hundreds of control and status lines and dozens of elements requiring configuration. To achieve operation in reasonable time frames, the system requires significant automation.

In general, the design of the control, safety and data acquisition systems follows the modular and scalable approach selected for the PFN modules. Each module therefore, contains within it a local controller, a local DAQ module and localized trigger control. This architecture provides for operation of the PFN modules in any combination from a single unit up to 83 simultaneous modules. Pulse shaping is achieved by triggering groups of PFN modules called segments, with precise delay times.

The systems chief safety requirement is the detection of critical faults, for example a bus or breech short, and the suspension of segment triggers that would occur after the detection of the fault. The Safety and Trigger Control systems are therefore designed to provide high-speed, precision fault and trigger signals

A. System Control

System Control provides for selection of operational modes, entry of launcher & projectile parameters, entry of test parameters, entry of diagnostic parameters, configuration of bank segment trigger timing, configuration of capacitor charging parameters, initiation of capacitor charging, confirmation of capacitor charge status, initiation of a shot and automatically securing the PFN system. Due to the hazards inherent in operation of a system with high stored energy, the control system must be fully deterministic and man-rated. Most control functions are non- or moderately time critical with the exception of the segment trigger timing and mid-pulse shutdown. Many commercially available industrial control and automation systems are fully deterministic and man-rated. They do not, however, provide the kind of high-speed precision timing required for mid-pulse shutdown. Therefore, time critical functions are allocated to the Safety and Trigger Control subsystems.

System Control utilizes commercially available industrial controllers, one each for each PFN Module, facilities and prime power. The local controllers are linked via fiber optic Ethernet and collectively comprise a distributed control system. Each local controller contains local intelligence sufficient for the PFN module, for example, to operate autonomously in the event of communication failures. COTS hardware is used to maximize system reliability.

V. SAFETY SYSTEM & TRIGGER CONTROLS

The Safety System continuously monitors the PFN system and facility status, interlocks and fault conditions. To meet the requirement of providing for mid-pulse shutdown under specific fault conditions, portions of the safety system are designed to provide a precision, high-speed inhibit signal to the Trigger control system.

The Trigger Control system receives a master trigger signal from the System Controller, generates high-speed, high precision segment trigger signals under a preprogrammed sequence and inhibits subsequent segment triggers in the event an inhibit signal is received from the Safety system.

The Trigger Control system is based on COTS delay generator devices that provide nanosecond-timing precision. The delay generators are programmed via RS-485 over fiber optic lines by the system controller. The delay generators are daisy-chained to pass a master trigger signal from the first to all subsequent devices with high precision. To initiate a shot the system controller sends a master trigger signal to the first delay generator in the chain. Each delay generator then sends a trigger signal to each of the PFN module switches at a pre-programmed delay time relative to the master trigger signal. This method relieves the master trigger signal of having to be high precision but ensures that all switch trigger signals are timed with high precision relative each other.

A. Data Acquisition

The Data Acquisition system acquires and archives shot data, and provides for subsequent data review. The data acquisition system then need only be a semi-automatic system, programmed with acquisition parameters prior to a shot, recording high-speed data signals during the shot and downloading and archiving the data at some unspecified time later.

The data acquisition system, similar to the System Control and Trigger Control systems, is based on COTS devices, one DAQ module for each PFN module connected via Ethernet over fiber optic lines. Each DAQ module is programmable, has multiple data channels and the capability to acquire signals and store them in internal memory until they are downloaded for review and archiving.

VI. SYSTEM PERFORMANCE

The system provides flexibility for pulse shaping by varying the trigger timing and the staging of different inductance modules. The current pulse can be a flat top, a linearly increasing pulse or a pulse shape that peaks in the middle. Additionally the pulse shape can be tailored to meet the requirements for barrels with different lengths, bore sizes and inductance gradients.

Overall system efficiency of the PFN is calculated by dividing the energy delivered to the gun breech by the total stored energy. In this case it is estimated that the total system efficiency for the PoC banks is ~ 68%.

The simulation shown in Fig. 5 indicates that a 20 kg launch package can be launched from a 12 meter long barrel with an L′ of .42 μH/m at a peak velocity of 2500 m/s and a peak current of 5.87 MA. This is while maintaining a peak acceleration of 35,000 gee (343 km/s^2). The bore cross-section is 135 mm x 135 mm square configuration.

This particular simulation in not considered to be the optimum solution for the system at 63 MJ muzzle energy, but is an example of a possible solution.

VII. ACKNOWLEDGMENT

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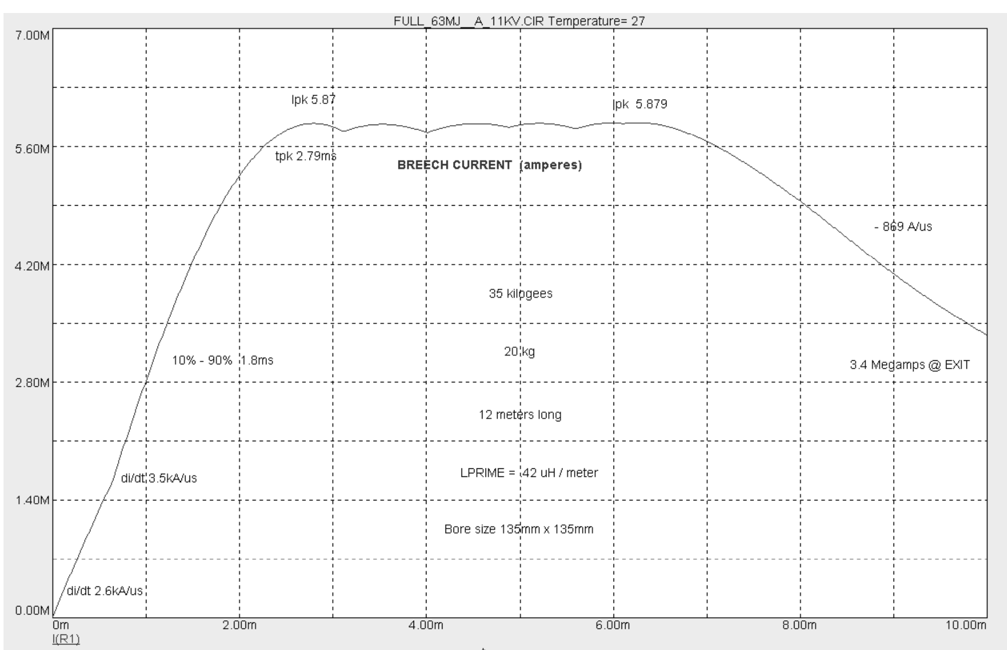

<u>*Barrel = 12m L′= .42μH/m Projectile Mass = 20 kg*</u>

Figure 5. 63 MJ Muzzle Energy - Current Vs Time